Detection of single-trial neonatal auditory evoked responses via spatial filtering

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1 Introduction

Several groups, including ours, have attempted to use MEG to record the fetal auditory evoked response. Because the recordings are so difficult to make, it is helpful to study the same signals in neonates. Neonatal auditory evoked responses (nAERs) are relatively easy to record because they have much larger amplitude; however, typically the recordings are quite variable due to changes in state and movement artifact. In such circumstances, averaging the evoked responses may give poor results. We have found, however, that it is often possible to detect the nAER with little or no averaging. In this work we investigate the use of a signal processing method known as linearly constrained minimum variance (LCMV) spatial filtering for improving the signal-to-noise ratio of single trial nAERs.

2 Methods

2.1 Data acquisition

The subjects were three neonates of conceptional age 40-46 weeks'. The neonatal MEG was recorded using the 37-channel lower sensor unit of a Magnes II biomagnetometer (Biomagnetic Technologies, Inc.). The auditory stimulus consisted of 1.5 kHz tones of duration 50 msec and intensity 60 dB. From each subject we recorded several runs consisting of 96 trials of duration 1 sec, with mean interstimulus interval 1.5 sec.

2.2 Data model

The sensor output, X(t), is assumed to be due to a superposition of current dipole sources plus noise:

$$X(t) = \sum_q H(q)M(q,t) + N(t)$$

where *H(q)* is a 37x3 forward matrix of rank two that maps the moment vector, *M(q,t)*, of a dipole at location q and time t to the sensor output. *N(t)* is the noise.

2.3 Linearly constrained minimum variance spatial filtering

The sensor covariance is given by

$$\begin{aligned} C(X) &= E\{(X-\overline{X})(X-\overline{X})^t\} \\ &= \sum_q E\{H(q)(M(q)-\overline{M}(q))(M(q)-\overline{M}(q))^t H(q)^t + Q \\ &= \sum_q H(q)E\{(M(q)-\overline{M}(q))(M(q)-\overline{M}(q))^t\}H(q)^t + Q \end{aligned}$$

where Q is the noise covariance. As applied previously to neural source localization [1], the LCMV method defines a filter $W(q_0)$ that minimizes the variance of the filter output power, $tr\ \{WCW^{-1}\}$, subject to the linear constraint, $W(q_0)H(q_0) = I$, which ensures that signal originating from location q_0 is passed. The solution is

$$W = (H(q_0)^t C(x)^{-1} H(q_0))^{-1} H(q_0)^t C(x)^{-1}.$$

2.4 Algorithm

LCMV filtering can be used to localize sources and to compute the temporal activity of sources, once their locations are known [1]. In the present study we know that the activity of interest arises from the auditory cortex. The purpose of applying the spatial filter is to increase the signal-to-noise ratio of the signals arising from this region. Instead of estimating the source location and using a linear constraint based on the forward solution, we apply a simpler method based on eigenvector constraints. First the averaged nAER is computed, and then principle component analysis is performed to decompose the signal into spatial components. The filter is constrained to preserve the first principle component, or eigenvector, H, corresponding to the largest singular value.

The filter, *W*, is the solution of a constrained minimization problem, where the constraint is $WH=H$ and the objective function is $tr\ \{WC(x)W^t\}$.

The precise formulation of W is

$$W = H\ (H^{t}C^{-1}H\ )^{-1}H^{t}C^{-1}.$$

The objective function, $tr\ \{WC(x)W^{t}\}$, can be thought of as the power of the filtered signal. Thus, this approach minimizes the output power while preserving the signal component with the desired spatial pattern. Upon applying W to the data, the output is reduced to rank one.

The effectiveness of the eigenvector-constrained method was assessed by comparing it with the conventional LCMV method, based on a forward solution constraint. We also assessed the performance of the algorithm when preserving more than one eigenvector and when using different parts of the data to compute the sensor covariance matrix.

Using the averaged nAER as a reference waveform, the correlation between the averaged nAER and the single trials was computed before and after filtering. To allow for variation in the latency of the signal, the signals were time-shifted up to 50 msec in order to obtain the highest correlation.

3 Results

The largest component of the averaged nAER had approximate amplitude 200 fT and latency 200-280 msec. Following band-pass filtering and removal of cardiac interference, the averaged nAER showed good signal-to-noise ratio, but the single trial nAERs were not easily resolvable.

The performance of the spatial filter was nearly the same for eigenvector constraints and forward solution constraints. Typically, the first principle component was dominant, accounting for as much as 98% of the total variance. Comparison of the eigenvector and the forward solution showed that they were nearly the same, as expected for a single dipole source. We also tried preserving more than one eigenvector, but this did not give a substantial signal-to-noise ratio improvement, even in cases when the first principle component not account for all the variance.

We investigated three different methods of computing the sensor covariance matrix. The first method used data from the prestimulus period when the signal was absent, the second used data from the poststimulus interval when the signal was large, and the third used the entire data. The differences between the methods were small. The third method, in which the entire data was used, was slightly better than the others, and was used to obtain the results presented below.

The spatial filter was first applied to the averaged nAERs in order to assess the degree of signal distortion produced by the filter. The result is shown in Fig. 1. The averaged nAER is virtually identical to the unfiltered nAER, demonstrating that the distortion was negligible, despite the fact that only the first principle component was preserved. The spatial filter was then applied to the unaveraged data.

Fig. 2 compares a 10-sec recording before and after spatial filtering. The filter is highly effective in removing interference and noise, allowing the single trial responses to be seen clearly. As a result of the increased signal-to-noise ratio, the spatially filtered single trials show a markedly higher correlation with the averaged nAER, as shown in Fig. 3.

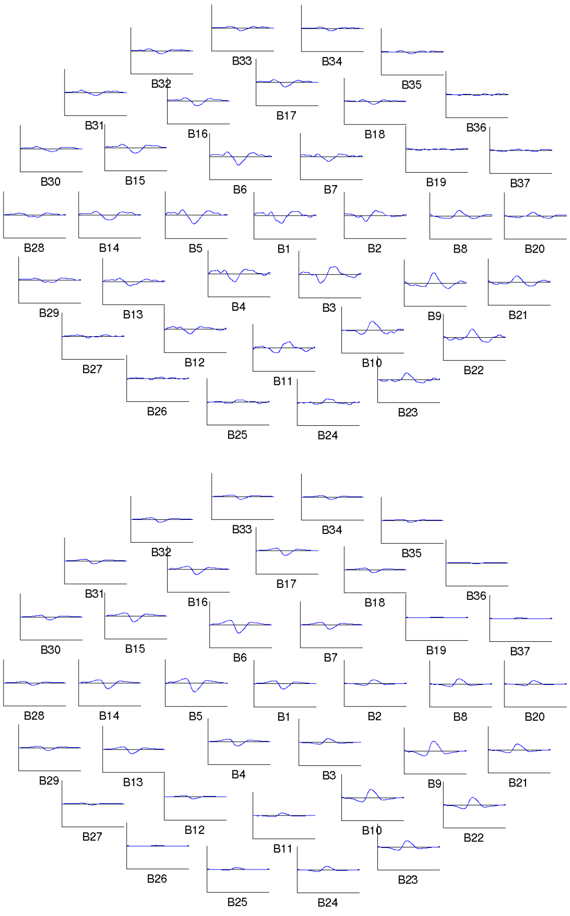

Figure 1: *Averaged nAERs before (above) and after (below) spatial filtering. The ranges of the vertical and horizontal axes are +/- 500 fT and 1 sec, respectively. The pre-stimulus interval is 250 msec. Notice that the signal after spatial filtering is virtually undistorted, even though it contains only one of the original 37 signal space components.*

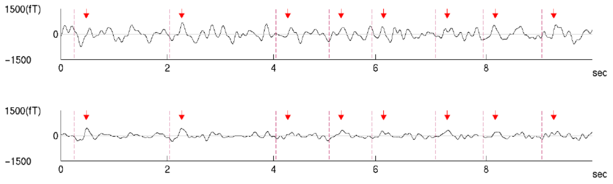

Figure 2. *Continuous MEG during a 10 sec interval before (above) and after (below) spatial filtering. The dotted lines indicate the time of the auditory stimuli. The arrows are drawn at the latency of the largest component of the averaged nAER.*

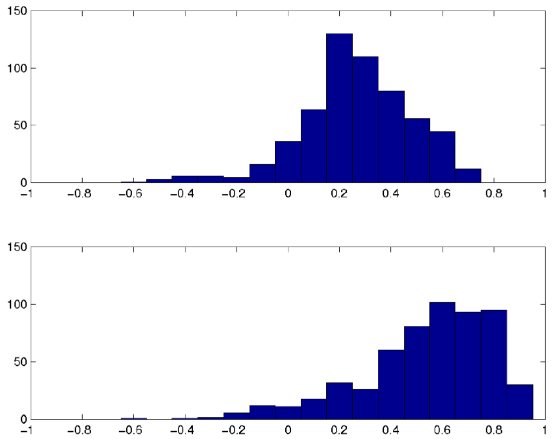

Figure 3. *Histogram of the correlations of the average waveform and the single-trials (top) before and (bottom) after spatial filtering.*

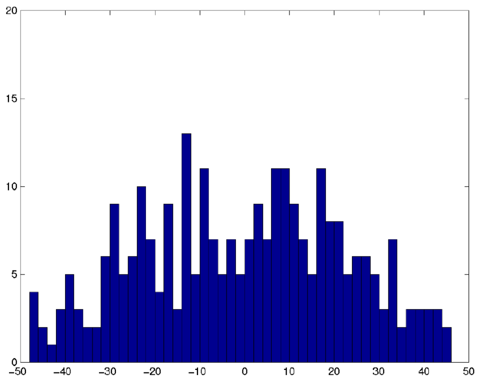

Figure 4. *The distribution of latency variations excluding outliers. The unit of the horizontal axis is msec.*

Fig. 4 shows a histogram of the latency variation, as determined from the time-shift required to maximize the correlation between the averaged nAER and each trial. The mean latency variation is less than 1 msec; the standard deviation in 23 msec.

4 Discussion

The spatial filter was highly effective in removing interference and noise from the single trial recordings. This could be seen from visual inspection of the recordings and also from the increased correlation between the single trials and the averaged nAER.

The algorithm used here was a modification of the conventional LCMV algorithm. Instead of using a constraint based on the forward solution, we used an eigenvector constraint, derived from principle component analysis. This simpler procedure was possible because the spatial pattern of the signal could be determined from the averaged nAER. The method is not susceptible to inaccuracies in the forward solution and virtually guarantees that the filter output will be highly correlated to the averaged nAER.

We compared the eigenvector-constrained method with the conventional LCMV method and found that the results were similar. This was not surprising because the eigenvector and the forward solution were nearly the same, as expected for a single dipole source. We tried preserving more than one eigenvector, but this was not helpful largely because most of the signal was accounted for by the first principle component. We also tried computing the covariance matrix using different parts of the data, but the results were similar, regardless of how the data were chosen. This implies that the character of the background noise was essentially the same throughout the data. Thus, for this study good results were obtained for the simplest implementation of the algorithm, in which only the first principle component of the signal was preserved and the entire data was used to compute the covariance matrix. For more complicated signals arising from several sources, it may be necessary to use more eigenvector constraints in order to preserve all signal components and to use a forward solution-based algorithm if it is desired to resolve the activities of the individual sources.

In summary, this study shows that spatial filtering can improve the signal-to-noise ratio of neonatal MEG recordings such that detection of single-trial auditory evoked responses is possible, potentially allowing the study of trial-to-trial variability.

Acknowledgements

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References

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